FULL SCALE TEST OF GROUTING AND FREEZING FOR NEW EXTENSION OF ROME UNDERGROUND, LINE B1

P. LUNARDI
Geo-engineering Design Office, Milan, Italy

F. LEONI
Rodio S.p.A., Casalmaiocco (Lodi), Italy

A. VALENTE
Rocksoil S.p.A., Roma, Italy

SUMMARY: In Rome, a full scale test by means of deep shaft and drift was carried out in order to aid the final design for the new extension of the underground railway, line B1.
The scope of the test was to define soil improvement methodologies for the construction of the new stations and specifically, to verify the applicability and the effects of grouting and ground freezing technique to the Rome subsoil.
The test was fully instrumented and monitored; furthermore, special laboratory tests were carried out to assess the physical and mechanical characteristics of the frozen soil.

1. UNDERGROUND RAILWAY, LINE B1 AND PURPOSE OF THE TEST

In the within of the preparation of the new subway lines in Rome (line C and B1), having stated from the preliminary soil investigation that the tunnels would have interested sandy to clay formation under high hydrostatic head, it was appeared endured absolutely necessary to study in detail the soil formation and their response to the foreseen ground improvement techniques. The designers have therefore recognised, jointly with the Municipality, the need to perform some deep shafts and drifts in order to intercept the soils and applying the construction techniques foreseen for the future works.
Under this program, "Annibaliano shaft" is part of the design of the underground railway line B1.Nevertheless, the shaft will be included in the complex of "Annibaliano" station, working as a service sunk-hole.

2. LAYOUT OF THE TRIAL TEST

The trial test includes (see figure 1):

- a shaft 25m deep, with the maximum diameter of excavation of 5.4m;
- a horizontal drift developed from the shaft for a length of 12m, with a ground cover of 15m and a face section of approximately 9.0 sqm (3.0 m x 3.5 m).

With the aim of the test to verify the compatibility and the adequacy of various types of ground improvement, the following treatments have been performed (see Figure 1):

- Built-up of jet-grouting crown in the upper part of the shaft (from down to –9.0 m).
- Built-up of the shaft grouting bottom plug and grouting face plug of the drift.
- Formation of frozen soil crown by Liquid Nitrogen, around the shaft performed from –8.00 to –30.00 m (overlapped to the overhanging jet-grouting treatment) and formation of frozen soil crown around the drift 16 m long, both ice-walls are 1 m thick.

The project began in November 1997 and completed in March 1999 including a stand-by period of about two months between shaft and drift activities (see Figure 6).

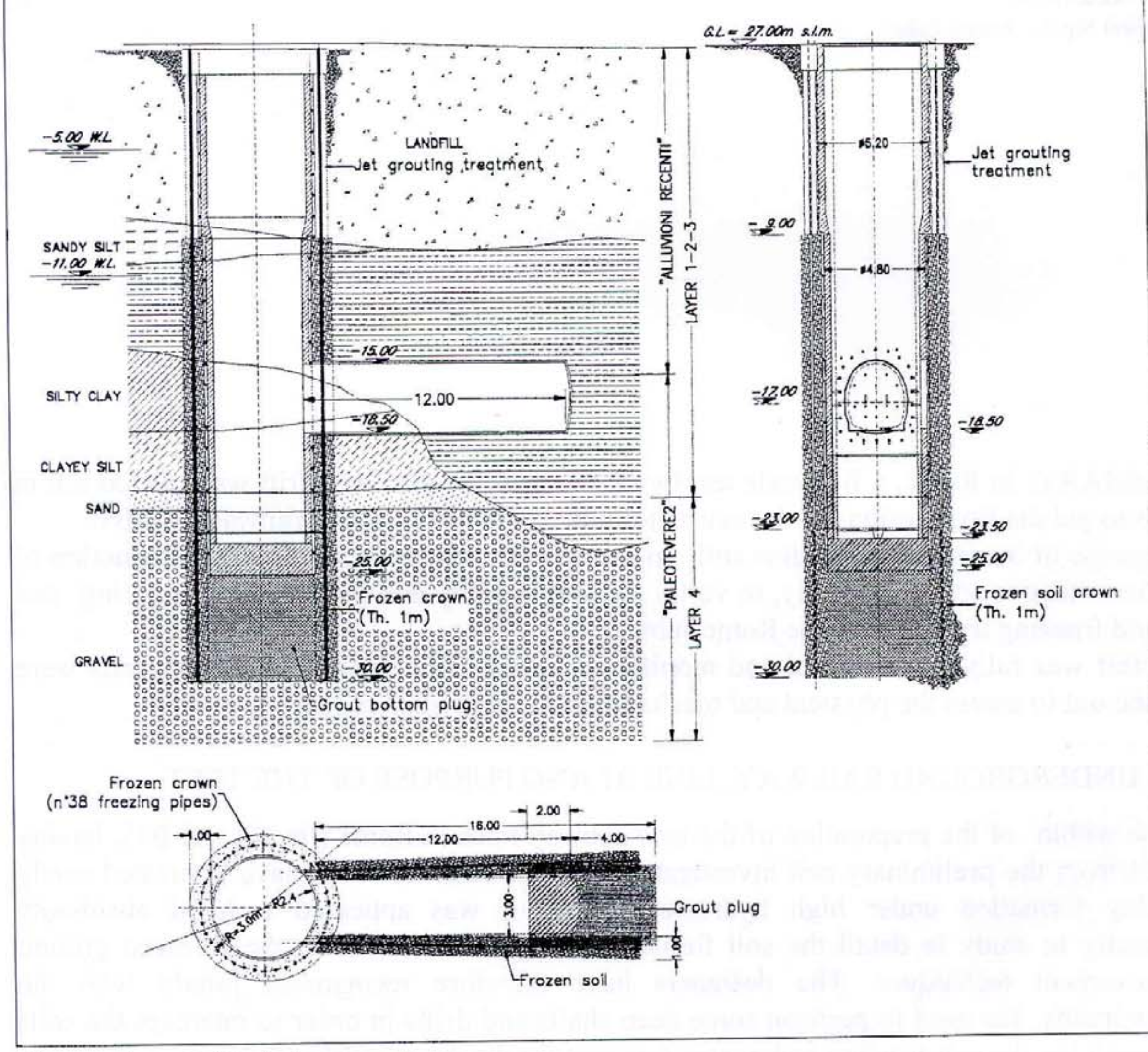

Figure 1: layout of the test

3. SUBSOIL AND HYDOLOGY CONDITION

Starting from the ground level of approx. elevation 27 m asl, the soil of the area is constituted as follow (see Figure 1) :

- **from g.l. to -8 m.** An heterogeneous landfill layer, constituted by a prevailing fine matrix, small blocks, bricks and hand-made fragments of various kind.
- **from -8,0 m to -15.0÷16.0 m approx.** The, so called, "Alluvioni recenti" deposits of the Aniene River and its affluent; Such deposits are characterised from prevailing sandy silt/clayey silt of color gray to dark, and quite plastic.

- **from -15,0÷16.0 m, to the shaft bottom.** The, so called, "Paleotevere2" deposits. Descending, they gradually change from yellow silty clay/clayey silt to continuous series of thin sandy/silty seams and becoming at the end as medium-fine gravel.

The drift has been located so as to intersect the Paleotevere2 deposit in perpendicular direction to the axis of the pre-existing pit of S. Agnese river. Along this alignment a tilted limit between the lowest formations is encountered.

The hydrology condition includes:

- an upper aquifer belongs to the "Alluvioni recenti" (w.l. at -5.0 m from g.l);
- a lower aquifer belongs to the "Paleotevere2" (w.l. at -11.0 m from g.l.);

4. SOIL INVESTIGATION AND LABORATORY TESTS AND MONITORING

Besides an extensive soil investigation and in-situ tests, for a better understanding of the frozen soil behaviour, some undisturbed samples were sent to a specialised laboratory for soil test under natural, frozen and thawed condition. It has to be highlighted that in the artificial ground freezing the following features have to be carefully considered:

- The frozen soil changes in mechanical properties after freezing and thawing;
- Volumetric changes are involved during the freezing process (frost heave);
- The frozen soil is typically strongly time , temperature and stress dependent.

The above mentioned matters, using special equipment and cold room, have been investigated under a specific sequence of tests:

- soil classification (as grain size, water content and Attemberg limits);
- uni-axial compression test (unfrozen, frozen at –10°C , -20° C and thawed);
- tri-axial compression test (unfrozen CU-UU, frozen at –20° CU and thawed CU);
- uni-axial creep test (frozen at –20°)
- frost heave test.

The first result of the laboratory tests has been a simplified classification of the materials formed by two prevailing families, called " **layer 1-2-3** " and " **layer 4** ".

In fact, with very moderate approximation and apart of the belongings to various geologic formations, the uppermost clayey/sandy silt of "Paleotevere2" are similar to the materials of "Alluvioni recenti" ; together they have been admitted as " layer 1-2-3 "; Instead, only the lowermost gravel of "Paleotevere2" casts the " layer 4".

LAYER	Wet Density (KN/m3)	Water content (%)	Saturation (%)	Porosity (%)	Unconfined compression strength (Mpa)		Young modulus (Mpa)		Drained condition ϕ/c (°/Mpa)		Undrained condition Cu (Mpa)	
	Unfrozen/ Frozen/ Thawed				Unfrozen	Thawed	Unfrozen	Thawed	Unfrozen	Thawed	Unfrozen	Thawed
1-2-3	16.9 2.03	25 45	85 99	40 55	0.07 0.28	0.06 0.25	4.8 16.3	2.2 16.3	30°/ 0.027	30°/ 0.012	0.03 0.048	0.03 0.12
4	21.6 22.7	10 11	80 95	22 26	nc	nc	nc	nc	36°/ 0.017	nc	nc	nc

Table 1: Summary of the soil properties

Range values of Classification and geo-mechanical data are summarised in the included Table1. Grain size distribution ranges of both soil groups are shown on Figures 2.

As reference of the strongly time dependent properties of the frozen soil, UCS strength and Young's Modulus evolutions for both groups are shown on Figure 3.
Upon the creep test results, the long–term properties have been evaluated considering a free standing time of the frozen soil varying from 6 hours to 2 weeks for the different frozen soil temperature of –10°C and –20°C.

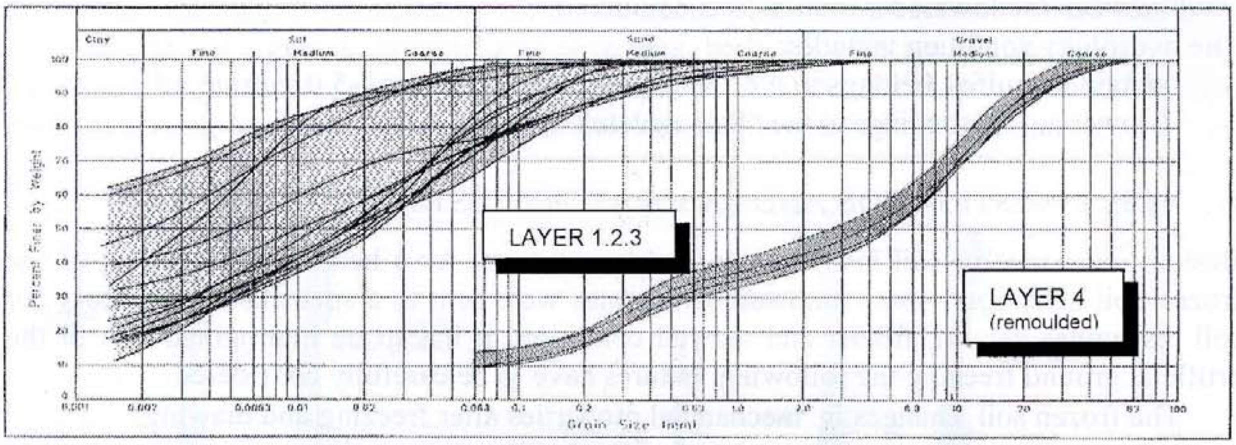

Figure 2: Grain size distribution

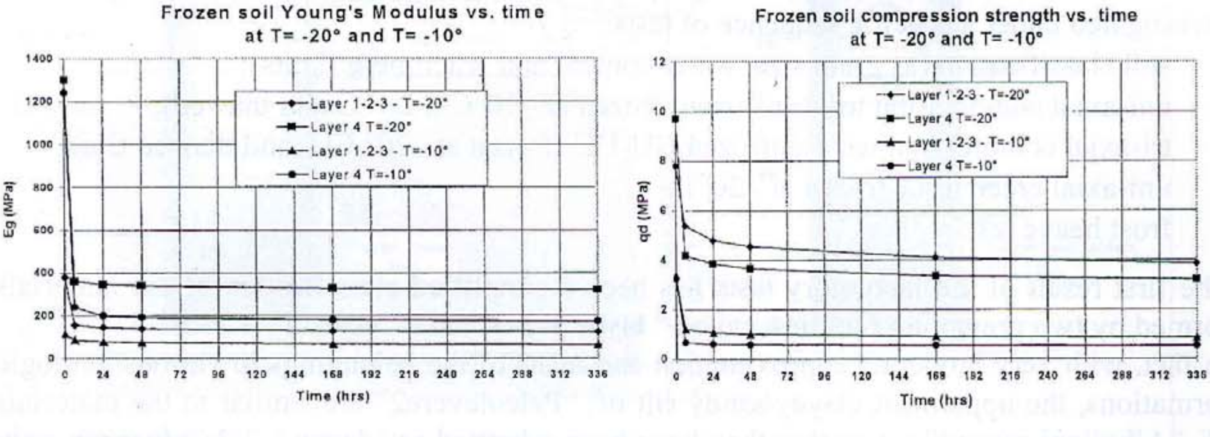

Figure 3: Frozen soil geo-mechanical properties

For the observation of the ground behaviour during the various phases and beyond the end of construction, a wide campaign of monitoring has been planned, including several surface benchmarks, multi-base extensometers, piezometers, convergence measurements during the drift excavation (Figure 6);
Both shaft and drift have been also instrumented in some sections by pressure cells and strain gauges. However, the sensors have been strongly affected by frozen environmental conditions.

5. SHAFT CONSTRUCTION

5.1 Shallow Jet-grouting crown and grout Blanket

The jet-grouting crown, performed by mono-fluid technique down to -9.0m from g.l., has interested only the landfill layer.
According to the designed geometry, overlapped elements with column diameter of 70-80 cm have been obtained, ensuring a good hydraulic water-tightness of the treatment.

The grout blanket of the shaft has been executed only through the gravel material of paleotevere2.
Although the first grouting phase was performed with cement-bentonite mixture with improved groutability ("Mistra'" grout), on the basis of volume and pressure criteria reached at that step, only with a second phase by inorganic sodium silicate based chemical grout (hard gel type, "Silacsol S") a fairer level of treatment has been achieved.
The total amount of the grout consumption of about 27% of the treated soil volume is in the range of the porosity value obtained in the laboratory test.
The water-tightness of the bottom plug, under 20 meters of hydrostatic level, has been confirmed during the excavation. By visual inspection of the excavated material, from depth –23.0 to –25.0 m, ground modification based on permeation and hydro-fracturing combined effect was verified.

5.2 Deep frozen soil crown

The frozen soil crown, by Liquid Nitrogen, has been executed from –8 m g.l to –30.0 m. interesting both the "Alluvioni recenti" and "Paleotevere2" deposits.

Owing the bore-hole instability during drilling and installation, a freezing element configuration formed by an external protection steel tube (dia 88.9 mm) and an inner copper freezing pipe was selected. The freezing pipes are accompanying with the jet grouting columns; so they were installed through the already upper grouted soil.

The deviation of totality of the holes was surveyed. With precise drilling operation a 70% of holes remained within the tolerance of 1% and only occasionally maximum deviation of 2% was reached.
Out of the designed thirty-eight freezing pipes 0.5 m theoretically spaced, two additional elements have been installed in order to comply the requirement of a maximum actual "window" between adjacent freezing pipes, at every depth, of about 1 m.
For soil temperature monitoring, no. 8 control pipes have been installed all around of the shaft. Furthermore, temporary inner piezometers have been also installed inside the shaft for additional checking of the reached closure of the ice crown and bottom plugging.

The freezing pipes were connected by series of two elements. The nitrogen exhaust gas have been maintained at approximately -100° C. For the attainment of the demanded thickness of the frozen wall, on the basis of the soil temperature judgement, the continuous feeding of liquid nitrogen lasted four days (from 16/4/98 to 20/4/98).
Upon the thermometric readings, a different behaviour of soils during freezing has been precisely identified.
The graphical representation of the temperature distribution (measured temperature vs. distance from the freezing pipe alignment at different time step) is a useful mean to appreciate the frozen wall progress in the two main different soil "layer" groups (Figure 4).
In fact, the diagrams, based on data pertaining to different layers (layer 1-2-3 with temperature readings coming from depth –10.0 m to depth –22.0 m, layer 4 with data coming from –26.0 to –30.0 m), reveal a faster development of the freezing process in the lowermost soil. It is therefore confirmed that in the gravel material of the "Paleotevere2" , a better heat transmission concurs to form a greater thickness of the frozen wall.
Given estimated thermal properties of the two different layers based on available laboratory information (Johansen method), a comparison between actual wall thickness progress and

calculated value (Sanger e Sayles method) has been worked-out with different freezing pipe spacing (0.5÷1.0 m). It shows a close agreement during the built up of the frozen wall (Figure5).

While the shaft has been excavated and temporary lined, the maintaining period with intermittent freezing last about 50 days (end date 10/6/1998). A substantial thawing of the frozen wall happened within about 30 days.

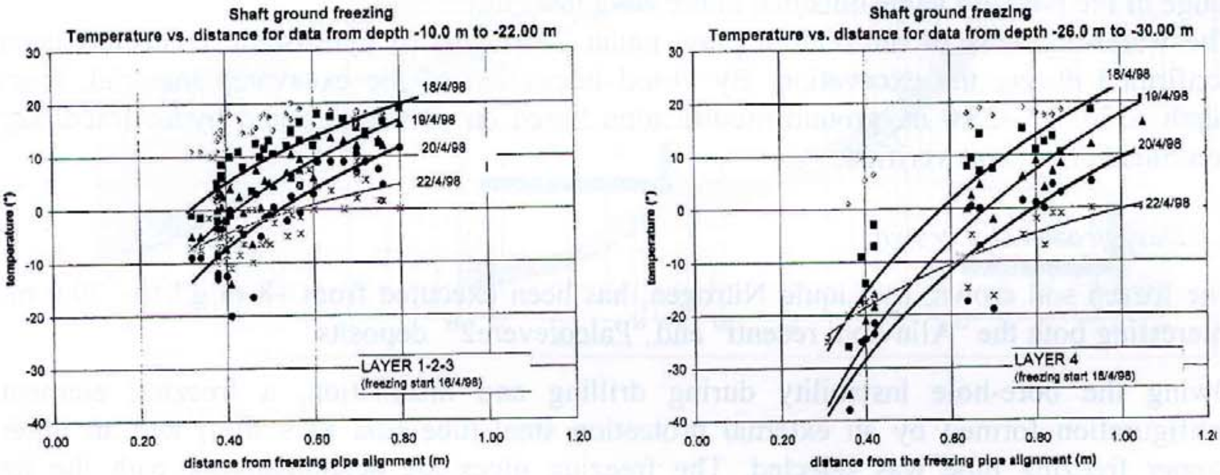

Figure 4: Temperature distribution of different soil groups

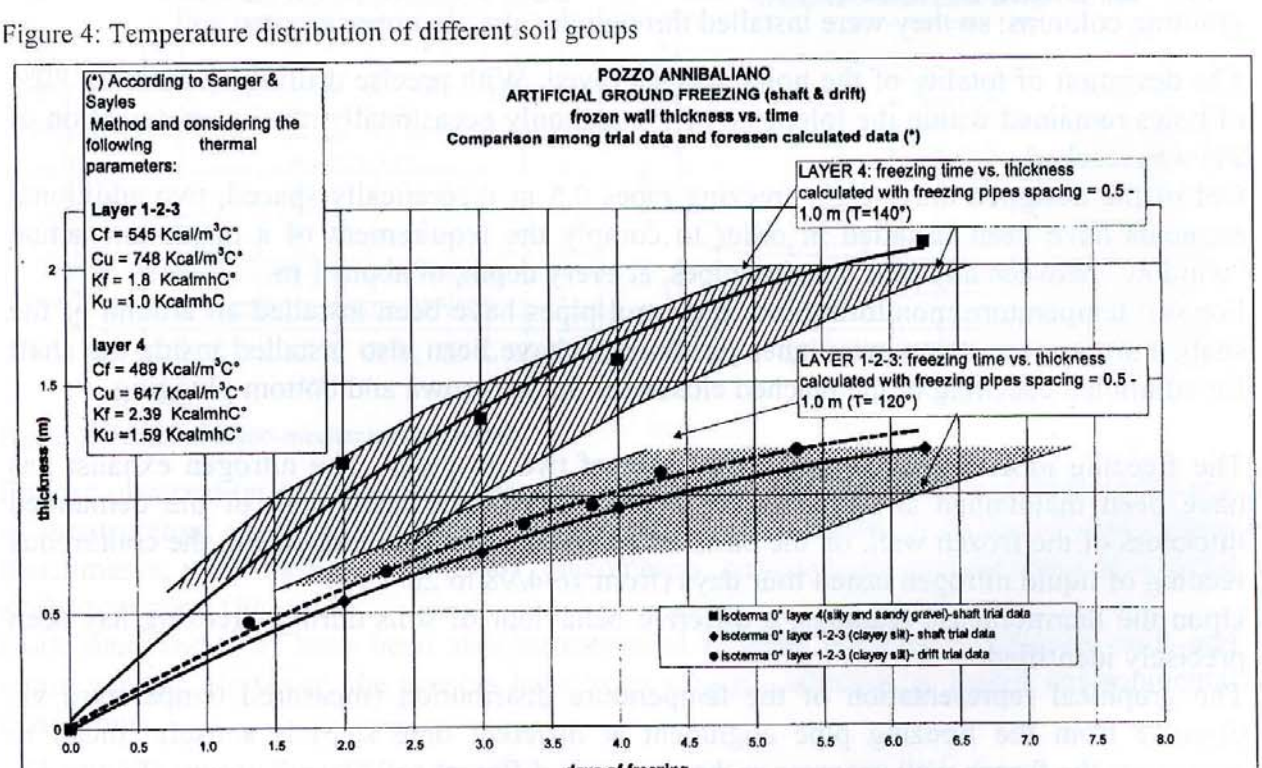

Figure 5: Frozen wall progress diagram

Surface levelling has revealed few millimetres of heave during freezing and suddenly retrieved during the shaft excavation. No effect has been monitored during the thawing period.

6. DRIFT CONSTRUCTION

An excavated stretch of 12m has been allowed by a frozen crown 16 m long with a face grouting plug 4.0 m thick.

As shown on the Figure 2, the subsidence of the area was closely affected by the drilling activities. Considering the experimental scope of the test, it has to remind that was intentional to drill initially without using any kind of "Preventer" leaving the way of water inflow and thus inducing phenomena of consolidation. Coming to the use of "preventer", the steady hydraulic conditions have been re-established and settlements dumped.

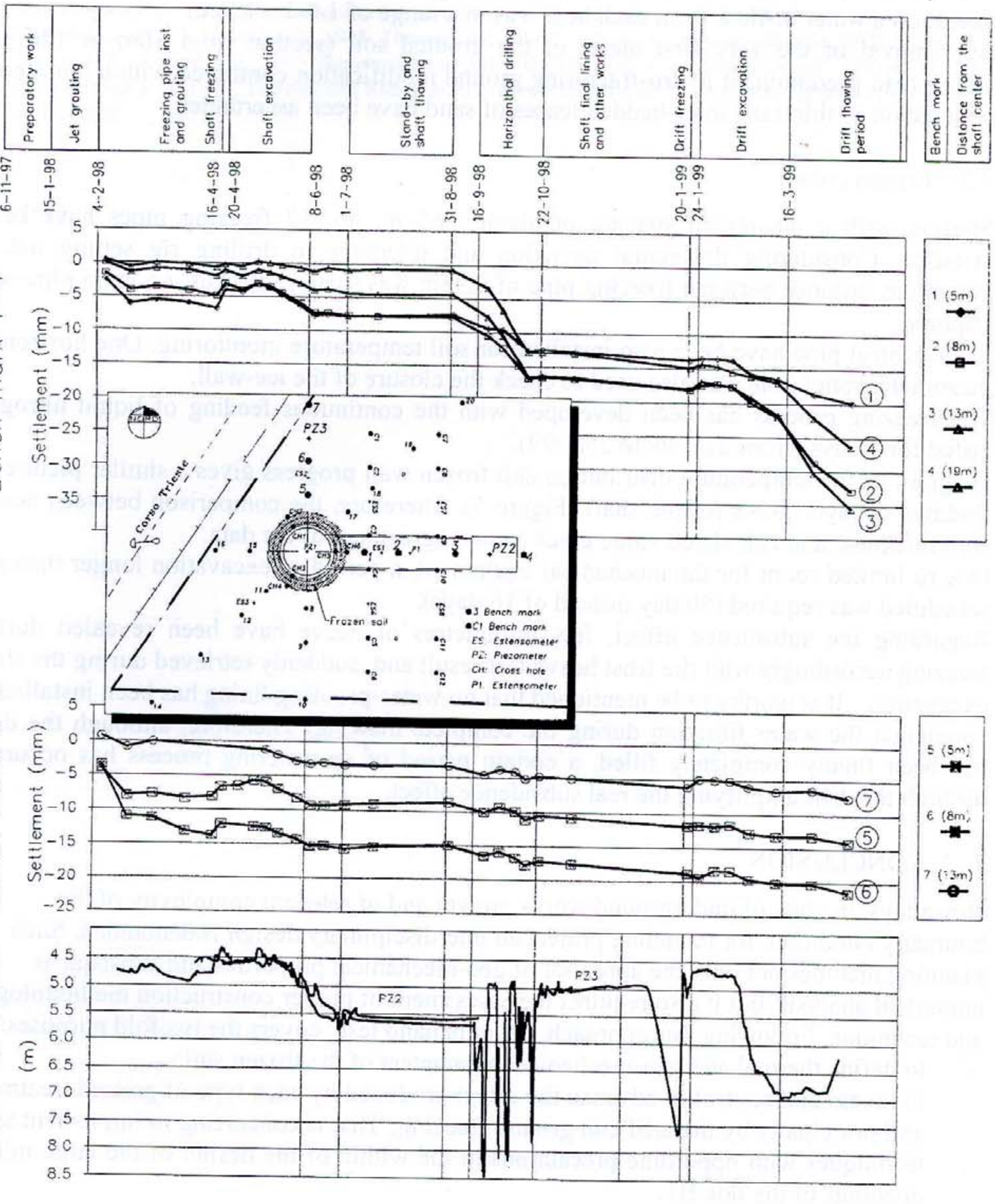

Figure 6: Activities and subsidence monitoring

6.1 *Grouting plug and face stabilisation*

No. 6 fiber-glass sleeved bolts and no. 7 "Tube a manchette" have been installed with the twofold purpose of face stabilisation and for reducing forehead water infiltration.

Grouting criteria and products have been based on the previous experience of the shaft plug, bearing in mind of greater amount of finer material of "layer 1-2-3".

With an overall consumption (by treated ground volume percentage) of 36% closed to the ground porosity given by laboratory test, the water-tightness of the face has been perfectly ensured during the drift excavation;

The beneficial effect of the grouting operation was evident considering that during drilling operation a water in-flow from each hole was in a range of 1.0-1.5 lt/sec.

By removal of the very first meter of the grouted soil (section from 10m to 12m), a widespread predominant hydro-fracturing ground modification combined with a good pore permeation of thin sand inter-bedded lenses of sand have been ascertained.

6.2 *Frozen crown*

Starting with a theoretical spacing of about 0.65 m, no. 17 freezing pipes have been installed. Considering the actual deviation and tolerance in drilling rig setting out, a maximum distance between freezing pipe of 0.95m was surveyed. Thus, no extra pipe was required.

No 4 control pipe have been also installed for soil temperature monitoring. One horizontal piezometer/relief hole was also used to check the closure of the ice-wall.

The freezing process has been developed with the continuous feeding of liquid nitrogen lasted for 4 days (from 21/1/99 to 25/1/99).

Diagram of the temperature distribution and frozen wall progress gives a similar picture of findings of layer 1-2-3 for the shaft (Figure 5). Therefore, the comparison between actual wall thickness and calculated value gives a good agreement of the data.

Due to limited room for the mechanical equipment, a period of excavation longer than the scheduled was required (50 day instead of 16 days).

Regarding the subsidence effect, few millimetres of heave have been revealed during freezing accordingly with the frost heave test result and, suddenly retrieved during the shaft excavation. It is worthy to be mentioned that no water-proofing lining has been installed to counteract the water filtration during the complete thawing. Therefore, although the drift has been finally completely filled, a certain period of de-watering process has occurred through the drift amplifying the real subsidence effect.

7. CONCLUSION

Nowadays, in view of underground works growth and of relevant complexity of the boundary condition, for tunneling project an interdisciplinary design is demanded. Such planning includes not only the appraisal of geo-mechanical properties and subsequent numerical analysis, but it also requires the assessment of proper construction methodology and technique. Following this approach, "Annibaliano test" covers the twofold purposes:

- to define thermal and geo-mechanical parameters of the frozen soil;
- to assess and control in advance the effect produced by each type of ground treatment and principally by the artificial ground freezing; That is concurring to implement such techniques with opportune precautions in the within of the design of the large mined openings of the line B1.

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